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Polarization mode switching in p-AlGaAs/GaAsP/n-AlGaAs diodes in presence of compressive stress

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Abstract. Numerical calculations and experimental results show that, for the broad range of tensile strained p-$Al_xGa_{1-x}As/GaAs_{1-y}P_y/n$-$Al_xGa_{1-x}As$ heterostructures widely used in commercial laser diodes emitting at 766 – 808 nm, polarization of emitted light may be extremely sensitive to external uniaxial stress due to the change of wave functions symmetry and possible optical transitions in the quantum well levels system. In some heterostructures with quantum well width of 10 nm and phosphorus content below 0.08, TM/TE polarization mode relation showcases a several times decrease and even dominant polarization mode switching under moderate compression of about 5 - 6 kbar in [100] and [110] directions. At the same time switching from TE to TM mode is possible under compression in [001] direction.

1. Introduction

In comparison with uniform compression, uniaxial stress magnitude that can be applied to a material is not very high and limited by sample fracture. However, being kept below this limit it often breaks the crystal symmetry and cause strong anisotropic effects in electron energy spectrum, transport and optical properties [1-4] that can not be observed under hydrostatic pressure. It was reported previously about electroluminescence spectra blue shift up to 27 meV in p-$Al_xGa_{1-x}As/GaAs_{1-y}P_y/n$-$Al_xGa_{1-x}As$ ($y = 0.16$) laser diode heterostructure under uniaxial compression up to $P \approx 5$ kbar along [110] direction [5]. According to the numerical calculations, this shift is connected with about 2% increase of effective optical gap.

In this paper we show both theoretically and experimentally that, on a level with this relatively moderate effect, dramatic changes could take place under uniaxial compression in correlation between transverse electric (TE) and transverse magnetic (TM) polarization modes of emitting light due to the change of wave functions symmetry. Though the influence of uniaxial stress on semiconductor laser polarization was investigated previously [6, 7], in the present paper we for the first time demonstrate the possibility of the efficient TE/TM polarization mode tuning and switching by uniaxial compression in different crystallography directions for a wide range of p-$Al_xGa_{1-x}As/GaAs_{1-y}P_y/n$-$Al_xGa_{1-x}As$ heterostructures with tensile strained quantum wells (QWs) of different thickness and composition. The numerical calculations are compared with experimental results.

2. Samples and experimental details

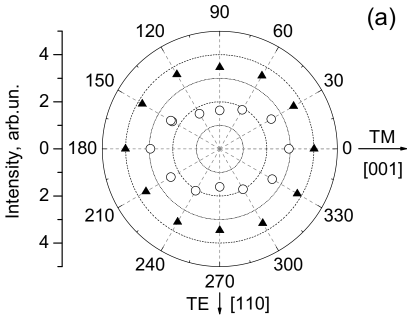
In the present experiment, the structures under investigation were grown on Si doped (001)-oriented GaAs substrates by metalorganic vapor phase epitaxy. The tensile strained $GaAs_{0.84}P_{0.16}$ QW with a width of 14 nm was not intentionally doped. It was embedded in 1000 nm thick $Al_{0.45}Ga_{0.55}As$ waveguide layers and 800 nm $Al_{0.70}Ga_{0.30}As$ cladding layers. The first 100 nm $Al_{0.45}Ga_{0.55}As$ around the QW were not intentionally doped. Then, the *p*- and *n*-doping started with 1×10^{17} cm^{-3} and increased up to 2×10^{18} cm^{-3} at the top of the cladding layers. Because of the strong built-in tensile strain in the $GaAs_{0.84}P_{0.16}$ QW of 0.58% arising during the epitaxial growth, the LH1 subband becomes the ground state of the valence band leading to predominant TM emission at laser operation.

Not being a conventional technique, the method of uniaxial compression of a sample firmly fastened in the elastic steel ring has been already mentioned in our previous papers [2, 4] and has been described in a special issue [8]. This approach is advantageous because of the axial distribution of the stress and a rigid fastening of the ends that protect the sample from premature destruction. The compressive stress may be applied in liquid nitrogen or helium with the help of a special device described in [8]. The magnitude of uniaxial strain (and stress) in the sample is determined using X-ray diffraction measurements [8].

The electroluminescence (EL) spectra were investigated at 77 K under uniaxial compression up to $P = 5$ kbar along the [110] direction in an optical cryostat with the uniaxial stress device inside. They were recorded using a PC controlled MDR-12 monochromator with a spectral resolution of up to 0.1 nm. Phase sensitive detection provided a dynamic range of operation for the system of up to five orders of magnitude. Noise and interferences limited the intensity region for a particular spectrum to the level of 10^{-2} - 10^{-3} of the maximum signal intensity. A Glan prism and thin-film polarizer were used for polarization analysis of the emitted light.

3. Experimental results

The intensity of light I in the plane normal to the heterostructure, taken at liquid nitrogen temperature, is represented in dependence on polarizer turn angle at $P = 0$ and 5.1 kbar in figure 1(a). Figure 1(a) demonstrates not only the strong increase of intensity under compression in [110] direction, but also evident decrease of relative TM/TE intensity anisotropy: from 1.8 at $P = 0$ to 1.2 at $P = 5.1$ kbar (that is a factor of 1.5). It has to be mentioned, that the spectral shift and the increase of the EL intensity with applied stress as well as the ratio between TM and TE modes (polarized perpendicular and parallel to the plane of heterostructure, respectively) were absolutely reversible in the investigated uniaxial stress interval under loading and unloading in different cycles of the experiment [figure 1(b)].



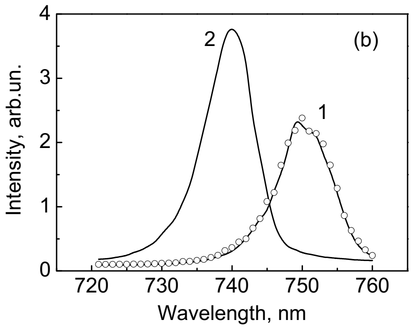


Figure 1. The light intensity in dependence on polarizer turn angle for the $GaAs_{0.84}P_{0.16}$ QW of 14 nm width under uniaxial compression along [110] at $P = 0$ (circles) and 5.1 kbar (triangles) (a) and EL spectra measured at polarizer turn angle 300º under $P = 0$ (before the loading) (curve 1), $P = 5.1$ kbar (curve 2) and $P = 0$ (after the loading cycle) (circles) (b).

4. Numerical calculations and discussion

Numerical calculations of uniaxial stress influence on the energy spectrum, wave functions, matrix elements of electron-photon interaction as well as the optical gain of TE and TM polarization modes in strained p-$Al_xGa_{1-x}As/GaAs_{1-y}P_y/n$-$Al_xGa_{1-x}As$ laser diode structures have been performed for a number of samples with different combinations of the phosphorus contents $y = 0 - 0.20$ (with 0.02 intervals) and the QW widths $d = 4$, 10, 14 and 20 nm. The calculations were carried out under uniaxial stress up to 10 kbar along [110], [100] and [001] directions at a temperature of 77 K. The Luttinger-Kohn Hamiltonian [9] with strain terms [10, 11] was self-consistently solved together with Poisson's equation for the electrostatic potential using the finite difference **k•p** method. Numerical calculations were performed using the program Heterostructure Design Studio 2.1 in the vicinity of the zone center at the Γ point. We used the model developed in [2]. In the calculations, internal strain as well as external strain effects were considered. The internal biaxial tension at $P = 0$ is considered to be determined by the lattice mismatch between the $GaAs_{1-y}P_y$ QW and the $Al_{0:45}Ga_{0:55}As$ barriers (not by the GaAs substrate).

For illustration of the uniaxial compression influence, figure 2 shows the strong change of the energy spectrum of light hole (LH) and heavy hole (HH) quantized levels h1, h2,… h7 in the QW (d = 4 nm, $y = 0.16$) [figure 2(a)] together with the analysis of LH and HH states mixing under the applied stress [figure 2(b)]. The results of calculations depicted in figure 2(b) demonstrate that the uppermost level h1 is a pure LH state at $P = 0$. After h1-h2 anticrossing at $P \approx 4$ kbar [figure 2(a)], the share of HH states dominates at level h1 [figure 2(b)], i.e. the uppermost level h1 in the QW starts to become almost of HH nature under uniaxial compression. At the same time h2 level, which is a pure HH state at $P = 0$, starts to become almost LH nature after h1-h2 anticrossing [figure 2(c)]. As a result, the change of the ground state symmetry in the QW removes the prohibition on the interband transitions only with the TM mode illumination. Therefore, we conclude that an essential change in the TE/TM mode intensity ratio occurs under uniaxial compression: the stronger the HH states admixture to LH states at the upper level, the larger the advantage of the TE mode.

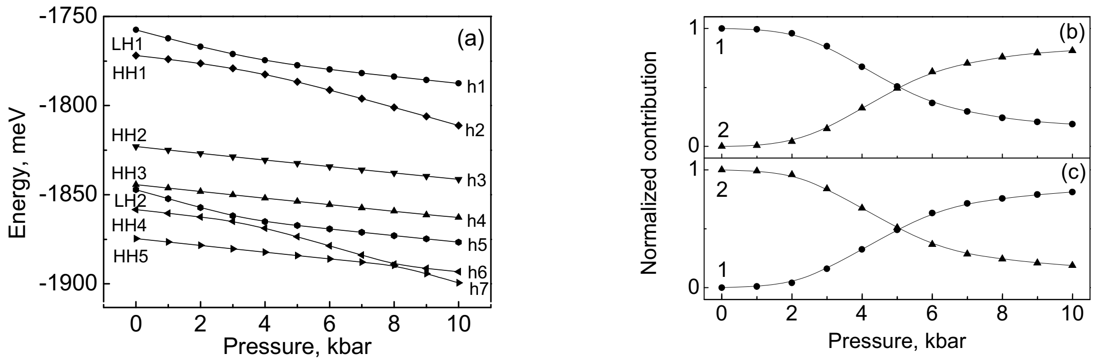


Figure 2. Calculated energy shifts of seven hole levels at the zone center under uniaxial compression along [110] direction (a) and pressure dependence of normalized contribution of basic functions with different angular momentum projection $m_J = \pm 1/2$ (curve 1) and $m_J = \pm 3/2$ (curve 2) into the wave function of h1 (b) and h2 (c) hole levels for the $GaAs_{0.84}P_{0.16}$ QW of 4 nm width.

After the calculation of the energy spectrum and wave functions, the program Heterostructure Design Studio 2.1 admits to introduce the scheme of possible optical transitions in the level system and calculates the matrix elements of the electron-photon interaction operator between two different states. The optical gain $g(\hbar\omega)$, which is in fact a negative absorption coefficient, is determined at the photon energy $E_{ph} = \hbar\omega$ according to the well-known method [3, 12]. The nonequilibrium carrier concentration $n = p = 10^{12} cm^{-2}$ in the QW was evaluated according to the average value of the injected current, ~ 10 mA [4].

In figure 3, we present the results of calculations for the experimentally investigated structure. Our analysis demonstrates that in the QW (d = 14 nm, $y = 0.16$) the optical gain g_{TM} of the TM mode at $P = 0$ is 8 times larger compared to the gain g_{TE} of TE mode. This fact is quite natural for a structure designed for TM emitting laser diodes. Under compression, the g_{TM}/g_{TE} ratio strongly drops (except for the case $P \parallel [001]$ direction). At the conditions of the present experiment ($P = 5.1$ kbar in [110] direction) $g_{TM}/g_{TE} \approx 5$ reveals a decrease by a factor of 1.6 that is in very good agreement with the experimental data (factor of 1.5) shown in figure 1(a). It should be noted that the TM/TE intensity ratio in a real laser operation is strongly determined by cavity parameters, and there is no direct proportionality between I_{TM}/I_{TE} and g_{TM}/g_{TE} ratios. Nevertheless, taking into account the fact that the lasing cavity practically is not changed under compression, we have very good agreement between calculations and experimental data.

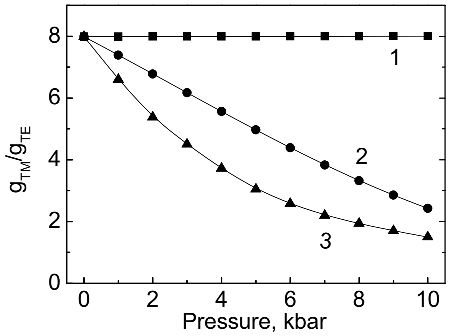


Figure 3. Pressure dependence of the g_{TM}/g_{TE} ratio for the $GaAs_{0.84}P_{0.16}$ QW of 14 nm width under uniaxial compression along [001] (1), [110] (2) and [100] (3) directions.

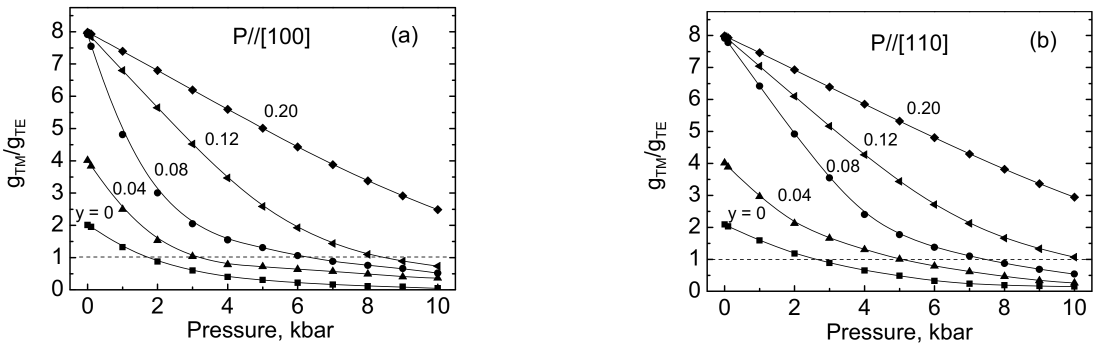


Figure 4. Pressure dependence of g_{TM}/g_{TE} ratio under uniaxial compression along [100] (a) and [110] (b) directions for structures with QWs of 10 nm width and phosphorus content ranging from $y = 0$ to $y = 0.2$.

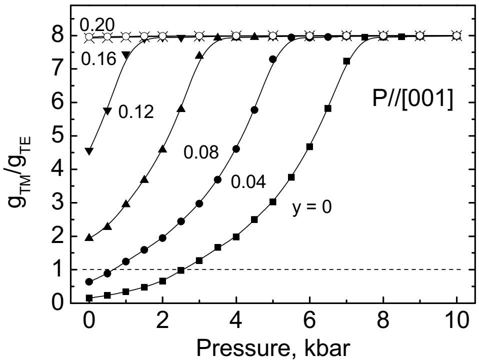


Figure 5. Pressure dependence of the g_{TM}/g_{TE} ratio in $GaAs_{1-y}P_y$ QWs of 4 nm width and phosphorus content ranging from $y = 0$ to $y = 0.2$ under uniaxial compression along [001] direction.

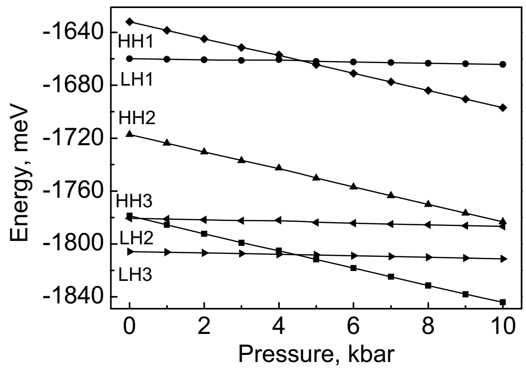


Figure 6. Calculated energy shifts of six hole levels at the zone center under uniaxial compression along [001] direction for the GaAs QW of 4 nm width.

Figures 4 and 5 demonstrate the results of $g_{TM}/g_{TE}(P)$ calculations in the structures with two different QWs: (i) $d = 10$ nm, $P \parallel [100]$ and $P \parallel [110]$ (figure 4) and (ii) $d = 4$ nm, $P \parallel [001]$ (figure 5), for a phosphorus content range of $0 \leq y \leq 0.2$. The results indicate a strong change of the g_{TM}/g_{TE} ratio under compression in the plane of the heterostructure both for $P \parallel [110]$ and $P \parallel [100]$. This effect is connected with the variation of the energy spectrum and symmetry of the size quantized levels in a QW, similar to the effects shown in figure 2. The most interesting result of our calculations is the indication that in the structures with rather small energy separation between the upper LH1 and HH1 states at $P = 0$, the TM $\rightarrow$ TE polarization mode switching is possible under relatively low pressure (figure 4).

In the case of compression along [001] direction that is perpendicular to the plane of the structures under investigation, wave functions do not change their symmetry, and light hole – heavy hole mixing in the Γ point does not take place for so called "light hole up" configuration of hole levels in a QW like represented in figure 2. If LH1 – HH1 energy difference Δ is large (for example, $\Delta = 43$ meV in the case depicted in figure 3, curve 1) g_{TM}/g_{TE} ratio does not depend on stress. At the same time, if HH1 is the ground level in a QW at $P = 0$ (see figure 6) and TE mode is dominant in the emitting light, compression along [001] direction can switch the output light from TE mode to TM mode emission (figure 5).

5. Conclusion

In summary, we have correlated experimental studies and numerical calculations to show that in laser diode structures based on $GaAs_{1-y}P_y$ QWs an effective TM and TE polarization modes tuning and switching under external uniaxial stress is possible. The best candidates for TM to TE switching are tensile strained heterostructures with low phosphorus content and narrow QW widths compressed in-plane along [110] and [100] directions (see figure 4). Switching from TE to TM mode is possible only under compression normal to the structure layers. The represented calculations are useful to anticipate and evaluate mounting and temperature induced strain effects on the diode laser performance [13,14]. A continuous tuning of TM/TE mode relation can be applicable in polarization spectroscopy of size quantized level states in QW structures. The demonstrated numerical analysis can be applied to many other layered QW structures of III-V semiconductor materials.

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